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Channel multiplier plates for image intensification

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Two-dimensional arrays of channel electron multipliers have recently been developed. These arrays can be used in image intensifiers to give high gain while spatial information is preserved. In this article, the performance of these channel plates is discussed and their application as image intensifiers in electron and X-ray detection, field ion microscopy and fast-switching photography is considered.

INTRODUCTION

Single channel electron multipliers (Refs. 1 to 4) have been used for some years to detect low-energy electrons, ions, ultraviolet radiation and X-ray photons, and then to amplify the resulting signal (Refs. 4 and 5). The principle of this type of distributed dynode multiplier is shown in Fig. 1.

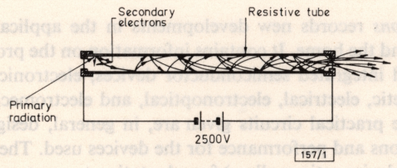

Fig. 1—Channel electron multiplier

The channel multiplier is usually made from a glass tube with a length of about fifty diameters. The inner surface is coated with a semi-insulating layer which is also a good emitter of secondary electrons. The resistance of the tube is chosen to be in the range 10^8 to $10^{14}\Omega$; the actual value is determined by the maximum output current which will be drawn from the device.

The channel multiplier is operated in vacuum with a potential applied between the electrodes. When an electron, or some other particle, enters the low-potential input and strikes the inner surface, several secondary electrons are produced. These electrons are accelerated along the channel axis by the applied electric field and move across the channel with the transverse component of their emission velocity. When they in turn strike the wall the collision energy is, on average, sufficient to produce several more secondary electrons. This process is repeated many times along the channel so that a large number of electrons leave the high-potential end of the tube. The gain of the multiplier depends on the applied voltage, on the ratio of the length of the channel to the diameter, and on the secondary emission yield characteristics of the inner surface. With a typical multiplier, the gain rises from about one thousand with 900V applied to at least 10^8 with 3kV across the device.

As the gain is determined by the length-to-diameter ratio of the channel and not by its absolute size, the dimensions can be scaled down without changing the performance. Such small multipliers can be assembled in close-packed arrays of parallel channels, called channel plates (Refs. 3, 6 and 7). These plates can provide multiplication while spatial information is maintained, so they are suitable for image intensification (Ref. 10).

The manufacturing techniques for channel plates are quite similar to those used for fibre optics (Refs. 8 and 9). Tubing of special glass is drawn down to the required diameter in one or two stages. In the latter case, many channels of an intermediate diameter are assembled and then the bundle is drawn down to the required size. The individual channels or multiple units are fused together to make up the required area, and the bundle is sliced into discs of the correct thickness. The faces of the discs are then polished (Ref. 10). After the inner surface has been prepared, the individual multipliers are connected in parallel by evaporating a thin Nichrome film at an oblique angle onto the two faces of the plate. The film connects the interstices between the channels, but leaves each multiplier open. A peripheral ring electrode is pressed against each face of the plate to make good electrical contact. Fig. 2 shows part of a channel plate composed of 40μm diameter channels. The distance between the centres of neighbouring channels is 50μm, the plate is approximately 2mm thick and has an open area of 60%.

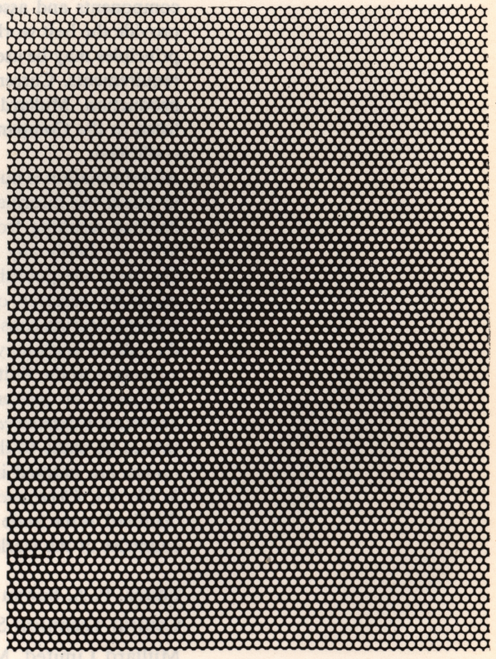

Fig. 2—Channel multiplier plate composed of 40μm diameter channels

This article is based on a paper presented at the 1969 Autumn Conference of the Association for High Speed Photography at Birmingham University.

CHANNEL PLATE PERFORMANCE

A wide range of measurements of channel plate performance have been made (Ref. 10). Plates composed of 40μm, 100μm and 200μm diameter channels have been studied in various demountable systems and also in sealed-off envelopes containing S20 type photocathodes.

Gain

The variation of the measured current gain of a plate, composed of 40μm diameter channels, with applied voltage is shown in Fig. 3. The plate has a length-to-diameter ratio of 60. With 5keV primary electrons at the input, the gain rises from about one thousand at 900V to 3×10^5 at 1600V.

For each value of applied voltage, there is an optimum value of the length-to-diameter ratio which gives maximum gain. Near this optimum the gain is least sensitive to the small variations in channel diameter which occur in practice, and so the spatial uniformity of the channel plate will be at its best. A value of the length-to-diameter ratio between 40 and 60 represents a suitable choice for imaging applications.

The useful gain which may be achieved with a channel plate is limited to about one million by ionic feedback (Refs. 4 and 5). Residual gas molecules near the output of the plate are ionised by electron impact. The ions are accelerated back down the channels and may start additional cascades by striking the channel wall near the input. The incidence of ionic feedback depends on the residual gas pressure and the electron density. At sufficiently high pressures and gains, a self sustaining discharge can occur. However, with pressures below 10^{-5} torr plates can be operated with gains in excess of 10^5 without trouble, while at 10^{-3} torr plates have been operated successfully with gains of several thousand (Ref. 11).

In single channel multipliers, ionic feedback effects are prevented by curving or spiralling the multiplier (Refs. 4 and 5). Any ions formed can move only a short way down the multiplier before striking the wall. The energy on impact is scarcely sufficient to produce secondary electrons, and those that are generated can hardly multiply in the available length of channel. In these single multipliers, gains higher than 10^8 can be achieved before the gain is limited by space charge effects (Refs. 12, 13 and 14). Although similar principles can be used in a channel plate, the construction

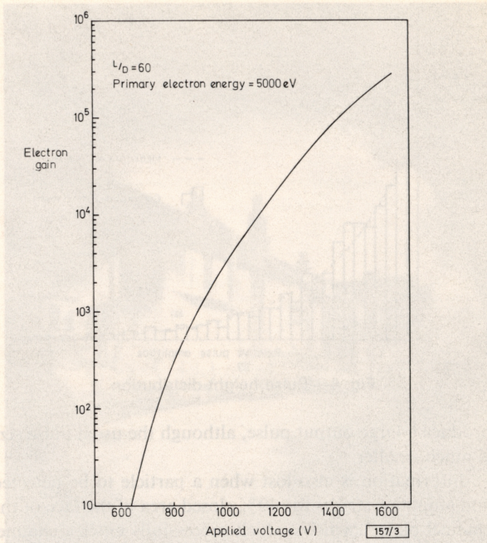

Fig. 3—Current gain of a channel plate as a function of applied voltage

of the device becomes complicated and the gain is increased at the expense of other properties. Two such methods will be mentioned, although their use in imaging devices is restricted.

Channel plates in which the axes of the channels are not perpendicular to the faces of the plate can be produced. If two or more 'angled channel plates' are cascaded with the axial directions opposed, ionic feedback to the input region of the first plate is prevented. The combination allows the maximum gain from the device to be increased, but some loss of resolution occurs as it is almost impossible to align the adjacent sets of channels exactly. Alternatively, arrays of sub-units, each made up of six channel multipliers twisted around a central solid rod, can be constructed (Refs. 15 and 16). These arrays have a lower open area than a normal channel plate, and their present spatial resolution capability is low. However, gains of approximately 10^7 have been achieved in this way.

Pulse height distribution

So far, the average gain has been implied whenever gain has been mentioned. In fact the gain varies from pulse to pulse because of the statistical nature of the multiplication process. The pulse height distribution is a measure of this variation. Fig. 4 shows the measured distribution from a channel plate and compares it with a computed distribution produced by a simulation of the statistics of multiplication. Both the experimental and the computed distributions have a negative exponential form. This type of distribution is characteristic of the channel plate and causes some information to be lost (Ref. 10) because although the mean gain is known, there is always some uncertainty about the number of particles at the input which has produced a particular number of electrons at the output. For instance, a single photo-electron may occasionally

In SI units, 1 torr = 133·322N/m²

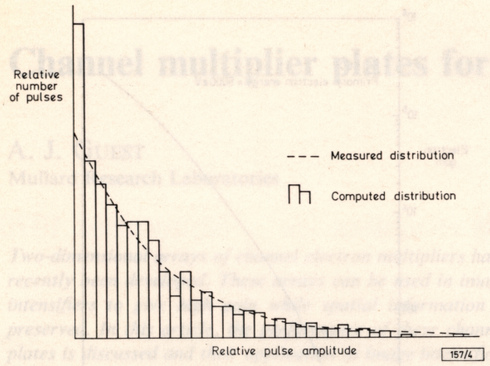

Fig. 4—Pulse height distribution

produce a large output pulse, although the usual pulse size is much smaller.

Information is also lost when a particle to be detected and amplified strikes the 40% closed area of the face of the channel plate. Particles which successfully enter a channel may still fail to produce secondary electrons when they strike the channel wall, or the pulse may die out after the first few stages. The detection efficiency of each channel, the ratio of output pulses to input particles, is a function of the angle and energy of the first collision and of the channel plate voltage. This parameter also depends on the nature of the incoming particle. It is usual to operate the plate near its maximum detection efficiency which, for electrons, occurs with input energies between 300eV and 10keV, with at least 700V across the channel plate.

The negative exponential distribution causes half the available information to be lost. With electrons as the input particles, the other losses reduce the information content by another factor of two. Consequently, to provide the same information, about four times as many input electrons are needed by the channel plate as by a perfect multiplier with the same gain. In other words, it takes four times longer to record an image with a channel plate intensifier than with an equivalent ideal system.

At very low input levels, the ultimate performance of the channel plate is limited by its background noise count rate. Spurious counts occur at a rate of approximately 0·01 to 0·1 counts/channel/sec. For a 50mm diameter plate made up of 40μm diameter channels, this is equivalent to an input current of less than 5×10^{-15}A.

Current transfer characteristics

The current transfer characteristics of a channel plate are shown in Fig. 5. With a resistance of $10^9\Omega$ and an operating potential of 1000V, the conduction current in the channel plate is 1μA. The transfer characteristic of the plate is linear for output currents up to 10% of the standing current. For higher input currents, the plate begins to show saturation effects, and the characteristic begins to curve over towards the horizontal. If the resistance of the plate remained constant, the output would saturate at a value close to the conduction current. However, the effective resistance of the plate changes slightly in operation because the cascade of electrons forms a parallel resistive path. This produces a more gradual saturation effect than might otherwise be expected and allows an output current to be drawn which can exceed the nominal conduction current of 1μA. As the individual multipliers in the channel plate are virtually independent of one another, each channel will saturate if the current drawn from it approaches its standing current.

The onset of saturation determines the maximum linear light output which can be obtained from a channel plate in combination with a phosphor screen at a particular accelerating voltage. For instance, with a typical phosphor efficiency of 20 lumens/watt and 8kV between the channel plate output and the screen, the limit to the linear light output with a plate resistance of $10^9\Omega$ is approximately 10·3cd/m². Acceptable images with some loss of contrast can be obtained at higher light levels. As channel plates can be made with various resistances, the saturation characteristics can be chosen to suit the application, provided the power dissipated in the plate is not excessive.

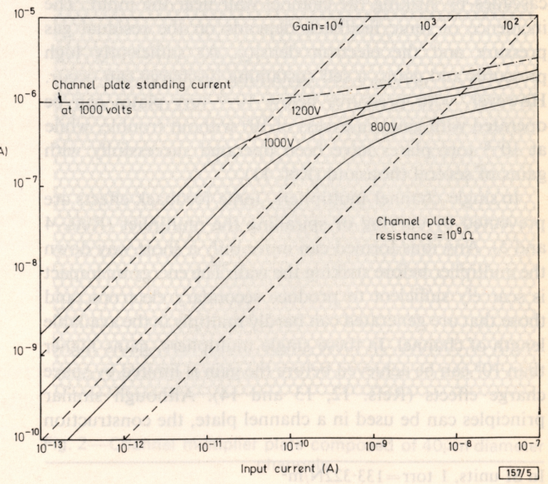

Fig. 5—Current transfer characteristics of a channel plate

Resolution

The resolution which can be achieved with a channel plate is determined by several factors including the channel diameter, the centre-to-centre spacing between channels and the electron optical focusing between the channel plate output and the phosphor screen. The hexagonal array structure of the channel plate starts to introduce spurious Moiré effects above a certain spatial frequency. These effects depend on the orientation of the array. For a channel plate composed of 40μm diameter channels, the spurious patterns begin to appear at a spatial frequency of 12 line pairs/mm.

Resolutions of this order have been achieved either by proximity or electromagnetic focusing of the electron image from the output of the plate onto the phosphor screen.

APPLICATIONS OF CHANNEL PLATES

Channel plates are compact, rugged and stable in air so that no special care is necessary for their storage. They are also compatible with most photocathodes. Thus they are suitable for electron optical imaging applications either in sealed-off image intensifiers or in demountable experiments which are frequently exposed to air.

Almost any type of image intensifier can be modified to contain a channel plate. For some years image converter and intensifier development has been concentrated on the more bulky magnetically-focused tubes and on electrostatically-focused inverter tubes (Ref. 18). Some of the demountable and sealed-off experiments with channel plates have used modified versions of existing tubes of this kind. Fig. 6 is a schematic diagram of an electrostatic inverter tube containing a channel plate. The potential difference between the photocathode and the anode creates an electrostatic lens which produces an inverted image. The image surface is curved, but when the channel plate is placed in a suitable position an acceptable image is formed. Fig. 7 is a picture taken from an experimental image intensifier of this type containing a plate composed of 40μm diameter channels. The distortion and loss of edge resolution are caused by the electron optics.

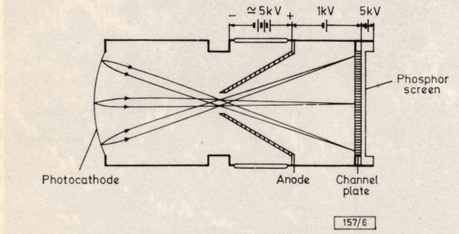

Fig. 6—Schematic diagram of an electrostatic inverter channel image intensifier

The channel plate is an efficient detector of low-energy electrons, so the potential difference between photocathode and anode may be as low as 3kV. In an inverter tube, the angles of collision of the photo-electrons vary across the face of the channel plate. This causes a slight variation in detection efficiency and there is a small darker disc where the electrons are travelling nearly parallel to the channel axes. This region is at the centre of the tube if the channels

Fig. 7—Photograph taken from the screen of an experimental image intensifier containing a plate composed of 40μm diameter channels

are perpendicular to the faces of the plate so it is usual to move it off the tube axis by angling the channels. The spatial non-uniformity has only a slight effect on image quality and can hardly be seen when a picture is displayed.

The simplest intensifier concept is the double proximity-focused electrostatic image tube, which is illustrated in Fig. 8. Electrons from the photocathode are focused onto the channel plate input by a strong electrostatic field across the small gap. Another strong field across a wider gap at the output focuses the secondary electron image onto the phosphor screen.

The field between the photocathode and the plate input is so strong that the electrons are travelling nearly parallel to the tube axis at the input. If the channels are also parallel to the tube axis, the photo-electrons tend to travel straight through without collision and no multiplication takes place. To correct for this, the channels in the plate are angled at about 10° to the tube axis so that the photo-electrons strike the continuous dynode surface near the input to the plate.

This type of tube is compact, has no distortion and there is no variation of resolution across the image. Until recently the proximity-focused tube, although simple in concept, has proved difficult to make because of the problem of introducing a photocathode into the confined space of the tube. However, by employing new techniques, L.E.P., the Philips Research Laboratories in France, are now developing a double proximity-focused channel image intensifier (Ref. 17) using a Mullard 27mm diameter plate containing 40μm diameter channels.

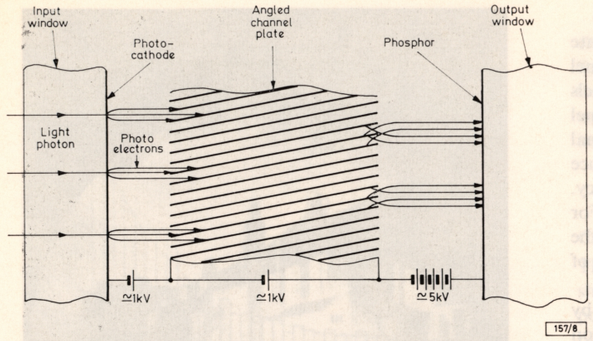

Fig. 8—Principle of the proximity–focused channel image intensifier

Fig. 9 shows an experimental X-ray channel image intensifier which also uses proximity focusing (Refs. 6, 7 and 10). Although the channel plate alone will detect clinical X-rays, the quantum detection efficiency is only a few percent; to improve the detection efficiency it is necessary to use an X-ray photocathode in the intensifier. The X-ray quanta are converted into light, which then produces photo-electrons from a suitable photocathode. This is a more complicated process but the efficiency may be so improved that several photo-electrons are generated by each X-ray quantum. The overall gain of the tube may exceed 2×10^4, and the output screen luminance should then be suitable for viewing under normal light conditions. and for taking moving pictures.

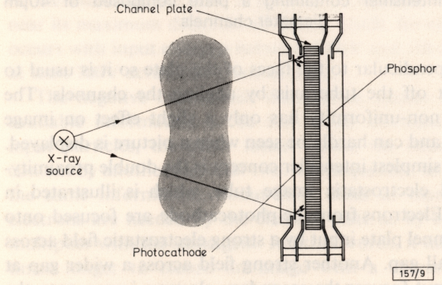

Fig. 9—Experimental X-ray channel image intensifier

One recent application of channel plates, in which the plate is incorporated in the apparatus and is frequently exposed to air, is in field ion microscopy (Ref. 11). Fig. 10 is a photograph of a field ion image which was taken at the Metallurgy Department, Cambridge University. A 27mm diameter channel plate containing 40μm channels was used to detect and intensify the image.

In the simple field ion microscope, a sharp point or tip of the specimen material is subjected to a high electric field in an imaging gas at low pressure. The field strength near the tip is greatly enhanced by the curvature so that the gas molecules are ionised and are accelerated towards a phosphor screen. The rate of ionisation around the tip varies with the local field intensity which is a function of its structure. Consequently, the ions produce an image of the crystal structure of the tip at the screen and it is possible to display details down to atomic dimensions. This process is limited by the low luminous efficiency of phosphors when bombarded with ions of many of the suitable imaging gases. When a channel plate is placed between the tip and the phosphor screen, it detects the ions with high efficiency and amplifies the image. With hydrogen or helium, the plate gives a performance equivalent to an external high-gain image intensifier but is more robust and considerably cheaper. The plate gives a superior performance with neon or argon, because its detection efficiency for these ions is nearly 100%—the usual phosphors are very inefficient for direct conversion of the energy of such ions to light. In this case, the luminance gain is improved by a factor of at least one million. In general, if the plate is operated at a current gain of one thousand, most field ion images can be observed in normal room lighting. Photographs which

Fig. 10—Neon ion micrograph of an iridium specimen which has been field evaporated in helium. Specimen at 7kV and 78K, 1000V across channel plate
$P_{Ne}=0{\cdot}5$ mtorr. $\frac{1}{2}$ sec exposure on Kodak Tri-X film (~400 ASA) with f/ 5·6

previously took hours, can now be taken in a few milliseconds, so that rapidly changing phenomena can be observed. The output image can also be recorded on cine-film.

An interesting fact about the field ion microscope used in the experiments at Cambridge is that the output image from the channel plate is focused onto the screen by combined electrostatic and magnetic fields (Ref. 11). The performance of the plate is not affected by the magnetic field.

Channel plates for high speed photography

The high resistance of the channel plate, together with its capacitance, means that the plate itself is probably unsuitable for extremely fast switching. If a channel image intensifier is to be used as a very fast shutter, it may be advisable to keep the plate running at a constant voltage and to shutter the input. This can be carried out with a grid, by switching the photocathode potential with respect to the plate input, or by optically coupling a conventional shutter tube to the front of the channel intensifier. A shutter grid seems to be the most suitable for an electrostatic inverter tube. In addition, a pair of deflection plates may also be incorporated in this type of tube for streak operation. Although the channel plate has its peak detection efficiency for electrons with energies near 1keV, it is still reasonably efficient for 10keV electrons. In streaked operation, the tube may be operated at the higher voltage to minimise transit time spread, or at a lower voltage to increase the deflection sensitivity.

A proximity-focused tube is probably the best for really high speed work. An experimental version of the L.E.P. proximity-focused image intensifier which has already been described can be operated as a shutter by switching the photocathode (Ref. 19). This tube has already been operated with an exposure time of 100ns and should be capable of even faster shutter times. It has the advantage of a high, variable gain and requires a comparatively low switching voltage with simple circuitry. The channel plate also acts as an additional opaque barrier to light feedback from the screen.

Another interesting tube which is under development at L.E.P. is an ultra-fast photomultiplier containing a channel plate (Ref. 20), illustrated in Fig. 11. Calculations indicate that the transit time for an electron pulse through a channel of length 2mm is less than 1ns and that the transit time spread should be about 250ps. This suggests that a channel plate can be incorporated in a very fast photomultiplier. In the design illustrated, the anode is matched to the output cable by a coaxial connection. The overall operating voltage is 3kV, and the measured transit time is 1ns with a rise time of 300ps. The gain is 10^5 but the energy resolution of the device is degraded by the information loss introduced by the channel plate. However, this photomultiplier should be very useful for observing very short, fairly bright events.

In addition to these uses of channel multiplier plates, various research groups throughout the world are considering numerous applications for plates in spectroscopy and as image intensifiers. In future, image dissector tubes based on this principle may be used for character recognition and information processing. Another application which looks very promising on paper is the use of channel plates in cathode ray tubes for high speed oscilloscopes. A plate of the correct resistance situated close to the screen would be suitable as a current amplifier. In this way, only a few input electrons would be needed to produce a bright spot on the screen. It should be possible to devise an oscilloscope which will have adequate screen luminance for recording single sweep, high speed transients on film with writing speeds in excess of 30cm/ns. High-frequency repetitive events should also be clearly visible with a duty cycle of only 1 in 10^6. Other advantages of using a channel plate in a cathode ray tube are the reduced beam energies and currents which are needed. These may also reduce the effects of deflection defocusing and should improve the deflection sensitivity.

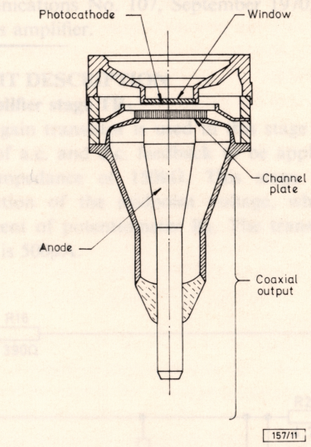

Fig. 11—Channel photomultiplier

Numerous uses of the channel multiplier plate have been mentioned in this article and these applications show that the device should have an interesting future. Although there is some loss of information when a channel plate is used, in most circumstances the advantages of a high-gain intensifier in a compact and robust form considerably outweigh this loss. The techniques of field ion microscopy have already been advanced significantly by the use of channel plates, so that a wider variety of imaging gases can be used and rapidly changing effects can be studied. In the future, the channel plate may be able to produce a similar improvement in other devices.

ACKNOWLEDGEMENTS

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15W class A audio amplifier

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Mullard Central Application Laboratory

UDC 621.375.029.45

This high-quality audio amplifier supplies an output of 15W into an 8Ω load or 20W into a 4Ω load, with less than 0·1% total harmonic distortion at 1kHz.

This high-quality audio amplifier is designed to operate in class A into an 8Ω load, giving an output power of 15W. With a 4Ω load, however, the circuit will operate in class AB to give 20W output power.

The transistors are all silicon devices which, except for the output pair, are plastic-encapsulated. The output transistors, a matched pair of BD181 devices, are driven by BC338 transistors which are preceded by a phase-splitting stage, using two BC147 transistors, and a pre-amplifier stage, a BC158.

The total harmonic distortion is less than 0·1% at full output. The amplifier will withstand normal overdrive conditions and does not require protection against short-circuit conditions.

The pre-amplifier described in Mullard Technical Communications No. 107, September 1970, may be used with this amplifier.

CIRCUIT DESCRIPTION

Pre-amplifier stage TR_1

A high-gain transistor is used in this stage to allow high values of a.c. and d.c. feedback to be applied, giving an input impedance of 150kΩ. This stage also provides stabilisation of the midpoint voltage, which is set by adjustment of potentiometer R_1. The transistor collector current is 500μA.

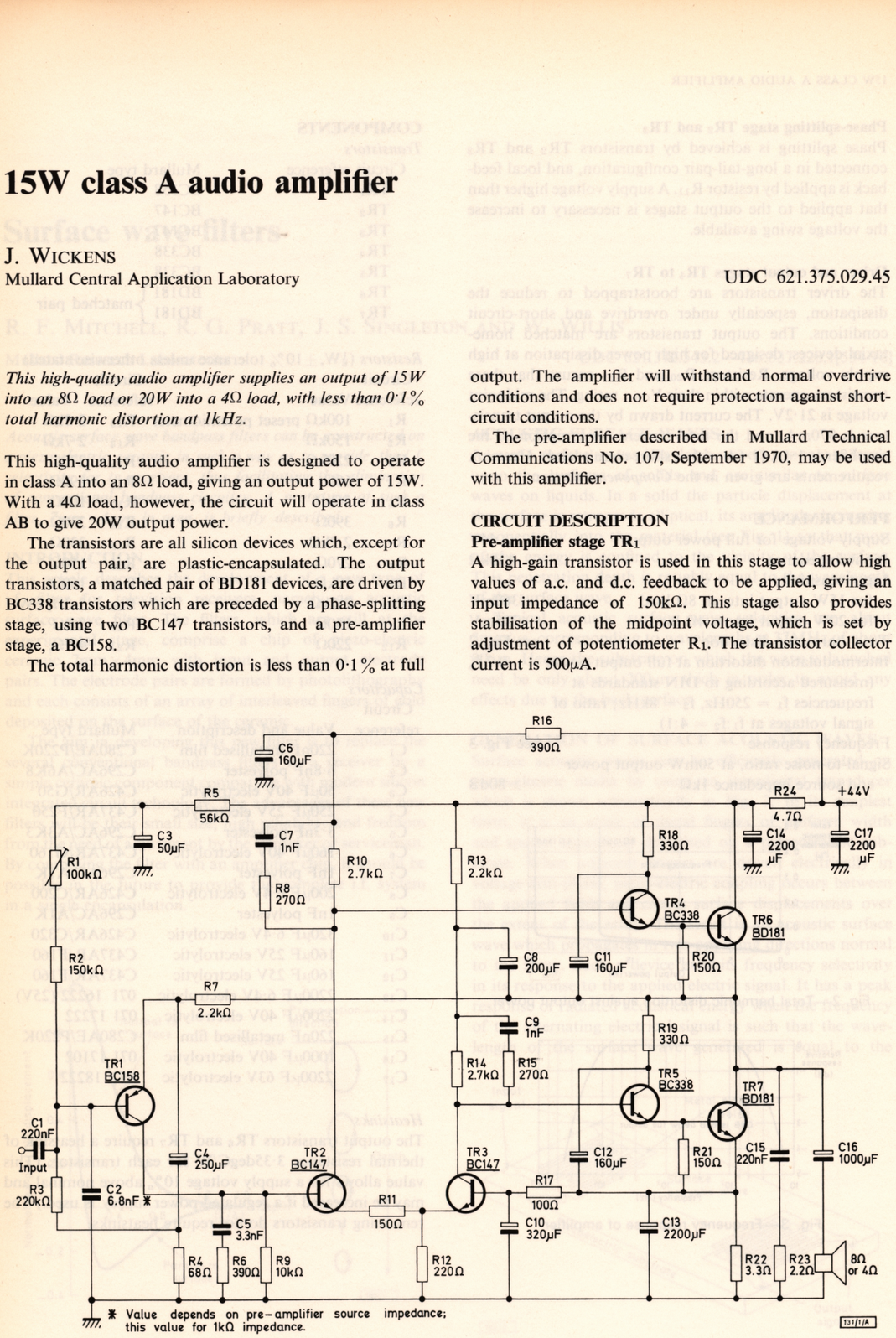

Fig. 1—Amplifier circuit

Phase-splitting stage TR_2 and TR_3

Phase splitting is achieved by transistors TR_2 and TR_3 connected in a long-tail-pair configuration, and local feedback is applied by resistor R_{11}. A supply voltage higher than that applied to the output stages is necessary to increase the voltage swing available.

Driver and output stages TR_4 to TR_7

The driver transistors are bootstrapped to reduce the dissipation, especially under overdrive and short-circuit conditions. The output transistors are matched hometaxial devices, designed for high power dissipation at high supply voltage. Resistors R_{20} and R_{21} ensure that these transistors operate within their V_{CER} rating. The midpoint voltage is 21·2V. The current drawn by the output transistors is 970mA, and the total current consumption of the amplifier is 1·1A (1·6A with a short-circuit load). Heatsink requirements are given in the *Components* section.

PERFORMANCE

Supply voltage for full power output	44V
Input impedance	150kΩ
Input sensitivity	
for 15W output into an 8Ω load	360mV
for 20W output into a 4Ω load	295mV
Total harmonic distortion	see Fig. 2
Intermodulation distortion at full output power (measured according to DIN standards at frequencies $f_1 = 250Hz$, $f_2 = 8kHz$; ratio of signal voltages at $f_1:f_2 = 4:1$)	0·2%
Frequency response	see Fig. 3
Signal-to-noise ratio, at 50mW output power and source impedance 1kΩ	>80dB

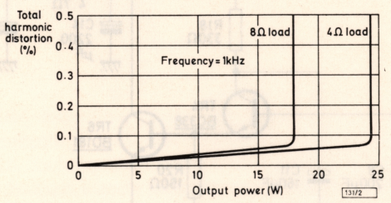

Fig. 2—Total harmonic distortion against output power

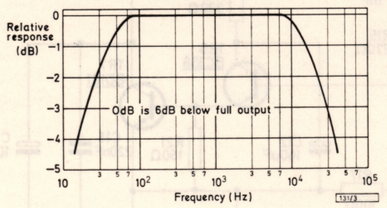

Fig. 3—Frequency response of amplifier

COMPONENTS

Transistors

Circuit reference	Mullard type
TR_1	BC158
TR_2	BC147
TR_3	BC147
TR_4	BC338
TR_5	BC338
TR_6	BD181 } matched pair
TR_7	BD181 }

Resistors (⅛W, ±10% tolerance unless otherwise stated)

Circuit reference	Value	Circuit reference	Value
R_1	100kΩ preset potentiometer	R_{13}	2·2kΩ
R_2	150kΩ	R_{14}	2·7kΩ
R_3	220kΩ	R_{15}	270Ω
R_4	68Ω	R_{16}	390Ω
R_5	56kΩ	R_{17}	100Ω
R_6	390Ω	R_{18}	330Ω
R_7	2·2kΩ	R_{19}	330Ω
R_8	270Ω	R_{20}	150Ω
R_9	10kΩ	R_{21}	150Ω
R_{10}	2·7kΩ	R_{22}	3·3Ω, 6W
R_{11}	150Ω	R_{23}	2·2Ω
R_{12}	220Ω	R_{24}	4·7Ω, 12W

Capacitors

Circuit reference	Value and description	Mullard type
C_1	220nF metallised film	C280AE/P220K
C_2	6·8nF polyester	C296AC/A6K8
C_3	50μF 40V electrolytic	C426AR/G50
C_4	250μF 25V electrolytic	C437AR/F250
C_5	3·3nF polyester	C296AC/A3K3
C_6	160μF 40V electrolytic	C437AR/G160
C_7	1nF polyester	C296AC/A1K
C_8	200μF 6·4V electrolytic	C426AR/C200
C_9	1nF polyester	C296AC/A1K
C_{10}	320μF 6·4V electrolytic	C426AR/C320
C_{11}	160μF 25V electrolytic	C437AR/F160
C_{12}	160μF 25V electrolytic	C437AR/F160
C_{13}	2200μF 6·4V electrolytic	071 16222 (25V)
C_{14}	2200μF 40V electrolytic	071 17222
C_{15}	220nF metallised film	C280AE/P220K
C_{16}	1000μF 40V electrolytic	071 17102
C_{17}	2200μF 63V electrolytic	071 18222

Heatsinks

The output transistors TR_6 and TR_7 require a heatsink of thermal resistance 3·35degC/W for each transistor. (This value allows for a supply voltage 10% above nominal and may be increased if a regulated power supply is used.) The remaining transistors do not require heatsinks.

Surface wave filters

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Mullard Research Laboratories

UDC 621.372.543.2—416:537.228.1[534-16]

Acoustic surface wave bandpass filters can be constructed on a piezo-electric ceramic in such a way as to provide the i.f. selectivity for tv receivers, thus facilitating the elimination of conventional bandpass circuitry. A prototype of such a filter, 7mm×4mm in area, is briefly described.

INTRODUCTION

This article describes the development of a new type of i.f. filter for television receivers, namely an acoustic surface wave filter. The filters, which are still at the experimental stage, comprise a chip of piezo-electric ceramic 7mm×4mm with input and output electrode pairs. The electrode pairs are formed by photolithography and each consists of an array of interleaved fingers of gold deposited on the surface of the ceramic.

The aim in developing this new filter is to replace the several conventional bandpass filters in a receiver by a simple ceramic component compatible with modern silicon integrated circuit technology. The advantages of these new filters will be their small size, high reliability and freedom from the need of adjustment by the setmaker or serviceman. By combining the filter with an amplifier chip, it should be possible in the future to provide the complete i.f. system in a single encapsulation.

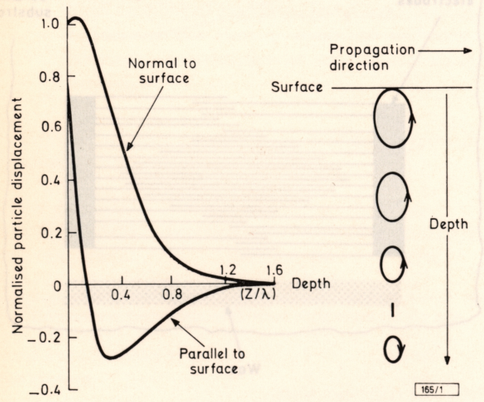

Fig. 1—Particle displacements for a surface-wave on material PXE4, polarised normal to the surface

ACOUSTIC SURFACE WAVES

Acoustic surface waves (Rayleigh waves) propagate freely upon the surfaces of solids and are similar to surface waves on liquids. In a solid the particle displacement at the surface is retrograde elliptical, its amplitude decreasing exponentially into the material (see Fig. 1) so that most of the energy is confined to the vicinity of the surface. This penetration depth is roughly equal to the wavelength of the surface wave.

Typical acoustic surface wave velocities are about 3mm/μs, corresponding to wavelengths at 37MHz of about 80μm. Hence the substrate on which the wave is launched need be only about 200μm thick in order to avoid any effects due to the back surface.

GENERATION OF SURFACE ACOUSTIC WAVES

Surface acoustic waves can be efficiently generated on piezo-electric media by using an interdigital transducer which is shown schematically in Fig. 2. In its simplest form, it is an array of metal fingers of uniform width and spatial separation deposited on a piezoceramic substrate. When adjacent fingers are driven electrically in voltage anti-phase, piezo-electric coupling occurs between the applied fields and causes surface displacements over the extent of the array. The result is an acoustic surface wave which propagates in two opposing directions normal to the array. Such a device exhibits frequency selectivity in its response to the applied electric signal. It has a peak response of radiated acoustical energy when the frequency of the alternating electrical signal is such that the wavelength of the surface wave generated is equal to the

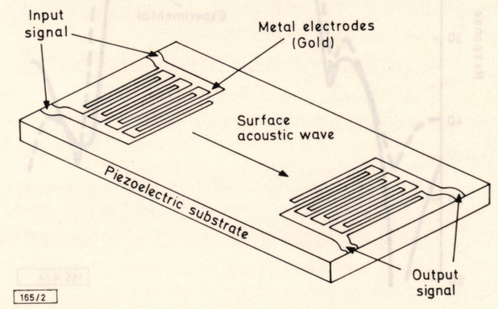

Fig. 2—Interdigital transducers on a piezoelectric substrate

periodicity of the array structure. In fact the frequency response of the simple uniform array is a well defined function of the form (sin x)/x. The degree of selectivity is readily varied by changing the number of finger pairs N used in defining the array. Numerically the effective acoustic Q is equal to N. Two similar arrays, suitably aligned on a piezo-electric substrate, with one as a generator of surface waves and the other as a receiver, will therefore act as a bandpass filter. Fig. 3 shows a typical response curve for two such arrays.

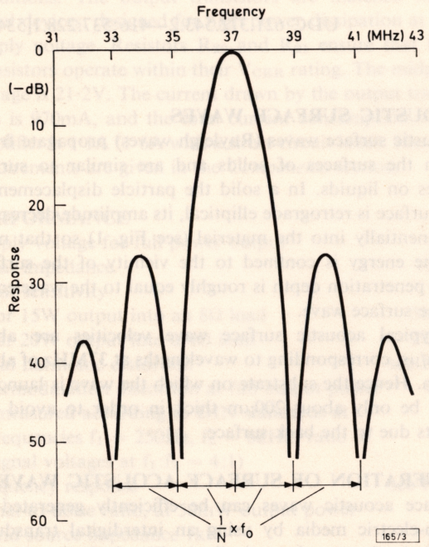

Fig. 3—Frequency response of a filter comprising two uniform arrays each having N = 17 and f_0 = 37MHz

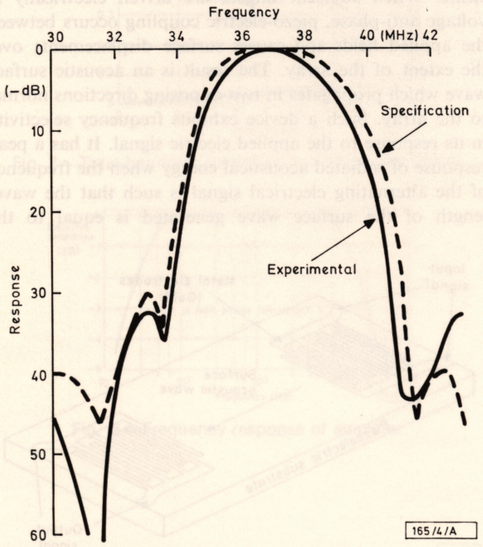

Fig. 4—Frequency response of surface wave filter for use in television receivers

The physical size of the transducers for the assumed operating frequency of 37MHz and 17 finger pairs on a typical substrate would be approximately 2mm × 2mm, with the individual fingers being 20μm wide. The transducers are fabricated by vacuum deposition and photolithographic techniques. Thus they are compatible with conventional integrated circuits both in size and technology.

FILTER DESIGN

The response required in the television i.f. system adopted in the U.K. is shown in Fig. 4, and this characteristic cannot be achieved with a single pair of transducers if uniform electrodes are used. However, the transducer response can be modified by altering the geometry of the electrodes. The design involves each of the electrodes being treated as a source of acoustic waves, the strength of the source depending on the electrode area. The acoustic output of the transducer is the result of the interference of the waves from each of these sources. The problem is to choose the strength and positions of the sources so that the interference is constructive over the required passband and

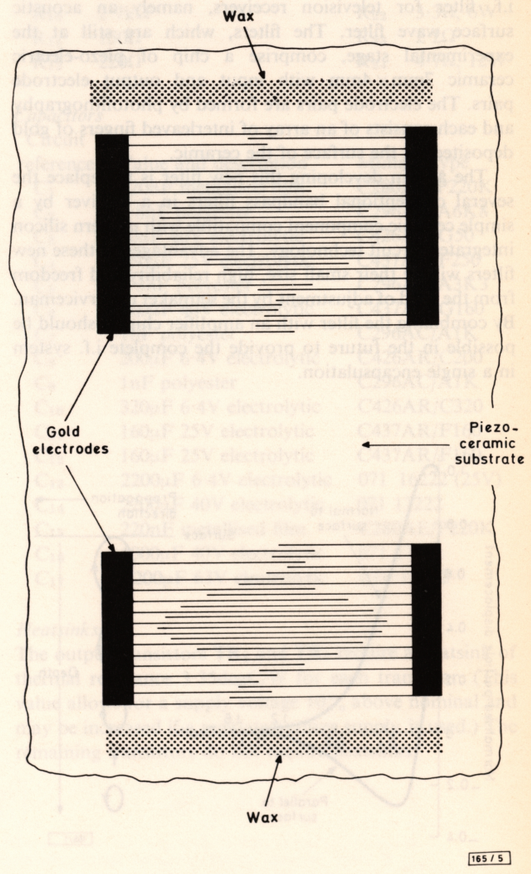

Fig. 5—Length-weighted filter

destructive elsewhere. This solution involves Fourier synthesis and computer optimisation techniques and is mathematically analogous to diffraction theory. Using such techniques, surface wave filters have been designed and made with a performance close to that required.

FILTER CONSTRUCTION AND PERFORMANCE

Fig. 5 shows the structure of a typical filter. The piezoceramic substrate used for experimental work is potassium sodium niobate which is polarised in the thickness direction. After the upper surface has been polished, the electrode pattern is formed by evaporation of gold and defined by photolithography. Unwanted reflected signals are reduced by a thin layer of black wax to about 50dB below the wanted signal.

The measured performance of a typical filter is shown in Fig. 4. The insertion loss of the filter is typically 20dB at centre frequency; incorporation of an integrated circuit pre-amplifier would prevent degradation of the signal-to-noise ratio. The group delay characteristic is theoretically flat, and measurements show variations over the passband of less than 50ns.

Although a number of prototype filters have been used successfully in a colour television i.f. amplifier, several problems remain to be solved, including the development of an optimum piezo-electric material.

Mercury cadmium telluride infrared detectors, at 5μm and normal ambient temperature

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UDC 621.383.4: 621.384.3

Infrared radiation at 5μm can be measured at room temperature with mercury cadmium telluride devices offering high detectivity and simplified amplifier design.

The performance characteristics of mercury cadmium telluride detectors in the 8 to 13μm band and at a temperature of 77K are already well established. Substantially background-limited performance can be achieved under these conditions. In this article, an investigation into the properties of these detectors in the 4 to 6μm band, at room temperature and with moderate cooling, is described. Detectors of various cutoff wavelengths within the 4 to 6μm band were made by adjusting the ratio of mercury telluride to cadmium telluride in the material. The detectors, of sensitive area 0·25mm square, were mounted on a ceramic substrate in a modified integrated-circuit flatpack.

At 5μm and a temperature of 77K the performance of mercury cadmium telluride detectors is comparable with that of indium antimonide devices. However, at room temperature (300K) indium antimonide is not ideal for applications involving transmission through the atmosphere because the material responds to 7μm, whereas the atmosphere is opaque beyond 5μm. Thus, much of the radiation emitted by broadband sources to which indium antimonide is sensitive is absorbed by the atmosphere. This investigation shows that not only are good detectivities achieved under these conditions with mercury cadmium telluride detectors, but resistance and noise levels are such that amplifier design is greatly simplified.

PERFORMANCE AT 300K

Detectivity

Fig. 1 shows measured values of area normalised detectivity D* (500K, 20kHz, 1) plotted against cutoff waveiength (defined as the wavelength at which the response is half the peak value), and calculated values of peak detectivity D* (λp, 20kHz, 1). It will be seen that the peak detectivity increases as wavelength decreases, reaching almost 10^{10}cmHz$^{\frac{1}{2}}$/W at 4μm. At 5μm the peak detectivity is typically $3{\cdot}5 \times 10^{9}$cmHz$^{\frac{1}{2}}$/W. (Indium antimonide detectors have a typical peak detectivity of 3×10^{8}cmHz$^{\frac{1}{2}}$/W at 6·5μm, which is close to the value obtained by extrapolation of the curve for the detectors under consideration.)

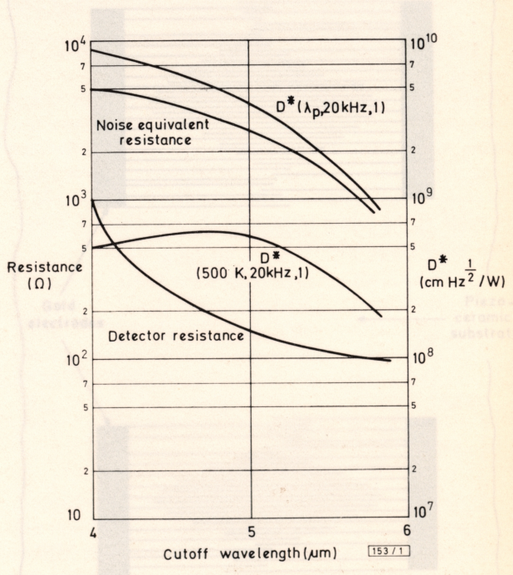


Fig. 1.—Variation of detectivity, noise equivalent resistance and ohmic resistance with detector cutoff wavelength

Noise and resistance levels

Fig. 1 also shows the typical noise equivalent resistance (defined as the resistance value which would give Johnson noise equal to that measured in the detector) plotted against cutoff wavelength. To obtain these values the bias current was chosen to give maximum detectivity. The detector ohmic resistance is also plotted to illustrate two advantages of these detectors:

1) The noise equivalent resistance is an order of magnitude higher than the ohmic resistance, so very-low-noise amplifiers are not necessary;

2) for the square elements used in this investigation the resistance levels are high enough to allow direct coupling to amplifiers, and it is not necessary to increase the element resistance by using a 'labyrinth' construction or to use transformer coupling.

Typical performance figures at two wavelengths are tabulated below.

Cutoff wavelength	4·7	5·6	μm
D* (λp, 20kHz, 1)	5×10^{9}	$1{\cdot}3 \times 10^{9}$	cmHz$^{\frac{1}{2}}$/W
Peak responsivity	1600	300	V/W
Noise equivalent resistance	4	1·25	kΩ
Resistance	200	100	Ω
Time constant	400	150	ns
Noise knee frequency†	2	5	kHz
Bias current	3	5	mA

†this is the frequency at which the low-frequency 1/f noise and white noise curves intersect.

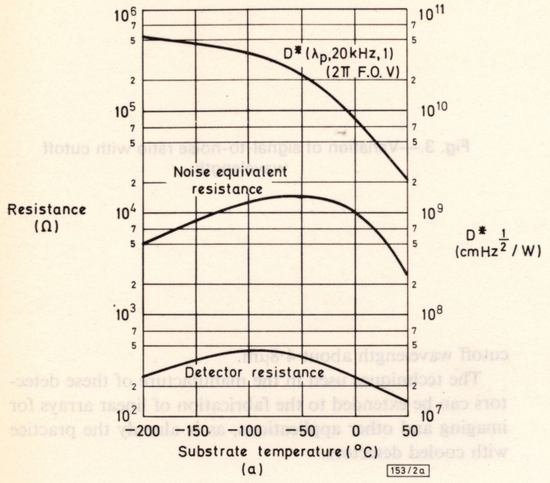
PERFORMANCE WITH MODERATE COOLING

Figs. 2a, 2b and 2c show the variation of detector parameters with temperature for a typical detector of cutoff wavelength 4·6μm at 300K. Increases in detectivity and responsivity are obtained if the detectors are cooled, and Fig. 2b shows that cutoff wavelength shifts to higher values. At −40°C the peak detectivity has reached 2×10^{10}cmHz$^{\frac{1}{2}}$/W and the responsivity has increased by an order of magnitude over the room temperature value. The high ratio of noise equivalent resistance to ohmic resistance is maintained. Further cooling to −196°C (liquid nitrogen temperature) gives a detectivity of 5×10^{10}cmHz$^{\frac{1}{2}}$/W, with a cutoff wavelength of 5·8μm, values which are comparable with figures for indium antimonide detectors. However, cooling to the −40 to −80°C region is likely to be of most interest, since these temperatures can be achieved with thermoelectric and freon cooling systems.

OPTIMISATION OF CUTOFF WAVELENGTH

For essentially monochromatic applications, such as spectrometry and gas analysis, the choice of detector cutoff wavelength is governed by the requirements of the measurement. If mercury cadmium telluride detectors are used, at room temperature, a response reaching only that required by the application will give the best overall performance.

However, in the case of detection or measurement of thermally radiating sources an optimum detector cutoff wavelength occurs, the value depending on the temperature of the source and being influenced by the spectral transmission of the atmosphere, especially over long ranges.



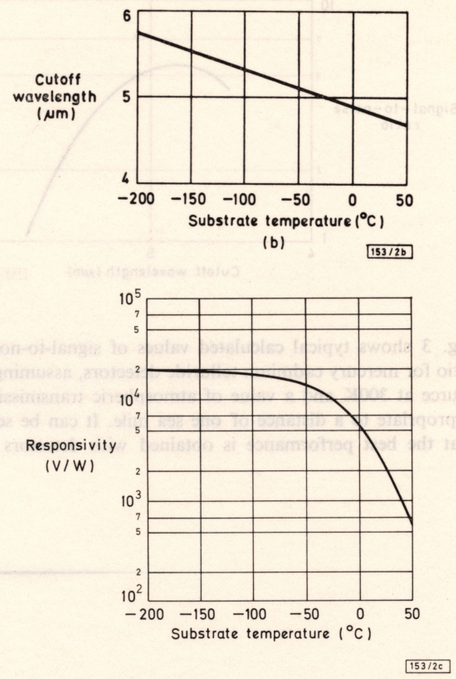


Fig. 2.—Variation with substrate temperature of

(a) detectivity, noise equivalent resistance and ohmic resistance

(b) cutoff wavelength, and

(c) responsivity

The material in this article was presented at the E.O.S.D. Conference, New York, September 1970 by Mr. Morten.

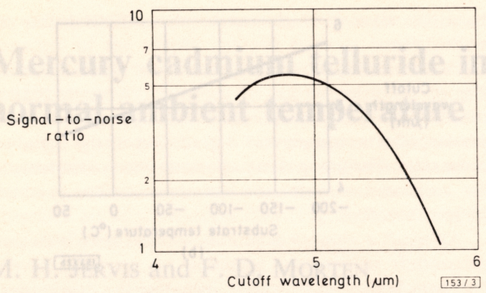


Fig. 3.—Variation of signal-to-noise ratio with cutoff wavelength

Fig. 3 shows typical calculated values of signal-to-noise ratio for mercury cadmium telluride detectors, assuming a source at 300K and a value of atmospheric transmission appropriate to a distance of one sea mile. It can be seen that the best performance is obtained with detectors of cutoff wavelength about 4·8μm.

The techniques used in the manufacture of these detectors can be extended to the fabrication of linear arrays for imaging and other applications, as is already the practice with cooled detectors.